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FRAGMENT AND DEBRIS HAZARDS

T. A. Zaker

Department of Defense Explosives Safety Board
Washington, D. C.

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Selected concepts involved in characterizing the hazards of fragment-producing ammunition are reviewed. Emphasis is placed on the effects from stores of ammunition which may detonate massively, such that the fragment field is potentially relatable to that from a single weapon detonated in isolation. Injury criteria in current use are compared, and a simple procedure for estimating injury probability as a function of distance from the explosion point is suggested.

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Technical Paper 12

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FOREWORD

This paper was prepared by the Technical Programs Division, Department of Defense Explosives Safety Board, as a brief review of selected concepts involved in characterizing the hazards of fragment-producing ammunition. Emphasis is placed on the effects from stores of ammunition which may detonate massively, such that the fragment field is potentially relatable to that from a single weapon detonated in isolation.

The present review of fragment hazards, though neither exhaustive nor conclusive, is intended to stimulate discussion of the subject in order to accelerate improvement in the classification and characterization of these hazards. Accordingly, critical comments on this subject and suggestions of alternate approaches will be welcomed.

P. F. KLEIN
Captain, USN
Chairman

July 1975

PREFACE

Methods for determining the initial velocity and mass distributions of fragments from effectiveness tests of explosive bombs and projectiles are reviewed briefly. The influence of the proximity of weapons to each other on the properties of fragments emitted from a stack is discussed. Techniques for calculating the ballistic trajectories of fragments considering atmospheric drag and gravity forces are outlined.

Injury criteria in current use are compared, and a simple procedure for estimating injury probability as a function of distance from the explosion point is suggested. When validated by tests designed for this purpose, the procedure may provide a rational basis for treating the hazards from fragment-producing ammunition.

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INTRODUCTION

The analysis of fragment and debris hazards is considerably less developed than techniques for predicting blast damage from detonation of a quantity of explosive material. Generally, while the effects of blast may be treated deterministically, the investigation of fragment effects requires a probabilistic approach. The reason for this is that the fragmentation process involves a degree of randomness in the phenomenon of fracture of metal case material surrounding the bursting charge. Hence the resulting fragment mass distributions cannot be predicted from an underlying elementary theory, and variations are to be expected in successive firings under ostensibly identical conditions. Moreover, given the random nature of the breakup of case material, and hence of the ballistic properties of fragments, terminal ballistic parameters such as the impact distance and velocity will also exhibit statistical variations. The terminal ballistic properties in turn determine hazard levels.

In what follows, the elements considered in the analysis of fragment hazards are outlined and, where possible, approximate relationships are given which may be helpful in estimating fragment hazards.

WEAPON FRAGMENTATION

The fragments emitted from detonation of a single weapon are characterized by the distribution of their number with respect to fragment mass, and by their initial velocities. Both the mass distribution and

the velocity are functions of polar angle measured from the nose of a munition assumed to be axially symmetric, such as a bomb or projectile.

Arena Testing

The distribution of number of fragments with respect to fragment mass, and their velocities, are determined experimentally by static detonation of single weapons in an arena of witness panels and recovery boxes containing material in which fragments are trapped, and from which they can be separated.[1*] Screening or magnetic separation techniques are used if the recovery medium consists of loose material such as sawdust. Fiberboard bundles or card packs, if used as fragment traps, are about a meter thick. They require disassembly and a tedious process of fragment extraction.

A plan view of a fragment test arena is sketched in Figure 1. Assuming an axially symmetric weapon detonated with its axis horizontal at the mid-height of the rectangular arena, it is evident that zones defined by intervals of polar angle will be projected as generally curved bands on the arena panels. Therefore the panels can be considered to receive fractional samples of the fragments emitted from the respective polar zones of the weapon. The sample ratio is determined from elementary geometric considerations, assuming rotational symmetry and assuming further that fragments travel in straight lines over distances of the order of arena dimensions. The arena radius is usually designed to be about 4 $m/kg^{1/3}$,

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* Superscript numerals designate appended references.

scaled by the quantity of explosive in the weapon under test. At this distance the blast pressure is about 0.7 bars.

Average fragment velocity in traversing the arena radius is determined by high-speed motion-picture photography of the exterior of the arena, based on the time interval between the light of detonation and the flash caused by fragments in perforating panels of aluminum alloy or mild steel less than 1 mm thick. Alternatively, the holes may be illuminated by photoflash bulbs enclosed between the panels and aluminum foil sheets serving as reflectors. The initial velocities of fragments in each polar zone are determined by correcting the measured average velocities for the effect of atmospheric drag over the distance traversed by the fragments (the arena radius) during the measured time interval.

Fragments extracted from the recovery medium in each polar zone are weighed individually and classified into groups defined by weight intervals specified in advance. Automatic systems have been developed to assist this effort. Earlier methods involved the use of standard-mesh sieves and approximate relationships between average weight in a weight group and its correlation with sieve size.

Mass Distribution

It is convenient to represent fragment mass data in the form of the cumulative distribution of the number N of fragments individually heavier than mass m, as a function of m. Such a function may be determined directly from the experimental results obtained by arena testing. An analytic expression commonly used to approximate such data is the Mott distribution:[2]

$$N = (M/m_o)\exp(-(2m/m_o)^{1/2})$$

where M_T is the total mass of all the fragments, and m_o is the average fragment mass. Sternberg[3] recently observed that the formula gives a reasonably good fit of the results from uncapped steel cylinders only in a central portion of the fragment mass range. On the other hand, the expression may simply be regarded as a two-parameter fit of fragment data, the values being chosen to fit best the range of fragment mass of greatest interest. Table 1, taken from Sternberg,[3] lists the average weight $\bar{M}$ of fragments weighing more than 1 grain (15.4 grains = 1 gram) from tests with uncapped, cold-rolled steel cylinders. For most explosives this average is about 1 gram.

As will be noted later, it appears that fragments from stacks of ammunition have generally coarser mass distributions than from single units detonated in isolation. Moreover, the largest fragments will be the most efficient ballistically. At distances of practical interest in the context of safety, therefore, it is the coarse end of the fragment mass distribution which will be of greatest concern. A distribution of the Mott form given above, but limited to representing the high-mass end of the fragment spectrum determined by tests, may be useful for summarizing and reporting fragment data, and in subsequently analyzing hazard levels.

Initial Velocity

The initial velocity can be determined from the average velocity obtained photographically from the time for fragments to traverse the arena radius in an arena test. Although a range of fragment velocity may be observed from fragments arriving successively at a witness panel in a given polar zone, in practice only a single value of velocity is usually reported

for each zone. This is because it is generally not practicable to observe specific fragments, to determine their velocities individually, and subsequently to recover them for analysis of their ballistic properties. To obtain such information experimentally would require exceptionally sophisticated procedures.

When it is not possible to make velocity measurements in fragmentation experiments, the velocity of fragments may be estimated from a formula credited to Gurney.[4] The basis for the relationship is an analysis of the dilation of a cylindrical or spherical shell under the action of internal gas pressure. This represents the expansion of detonation product gases under the assumption of uniform but time-varying pressure and density, and a linear velocity profile, as in the classical Lagrange problem of interior ballistics.[5] The result of the analysis is the formula

$$V^2 = 2E /(M/C + n/(n + 2))$$

where $(2E)^{1/2}$ is the Gurney velocity, a constant for a given explosive. M/C is the metal-to-charge weight ratio, and $n = 1$, 2, or 3 for plane, cylindrical, and spherical symmetry. Figure 2, taken from Kennedy[5], is a plot of this expression and of the formula for an asymmetric plane case as well. Table 2, taken from Jacobs[6], is a recent compilation of values of $V_g = (2E)^{1/2}$ from analysis of measurements in experiments conducted at the Naval Ordnance Laboratory (NOL) and at the Lawrence Livermore Laboratory (LLL).

<u>Stack Effects</u>

There are strong indications that the fragmentation characteristics of stacks of weapons differ significantly from those of a single unit

detonated in isolation. In general, large fragments are relatively more numerous than from a single unit. The effect is apparently more pronounced for weapons with small charge-to-metal ratios (artillery projectiles)[7,8] than for demolition bombs.[9] In addition, the velocity of the leading fragments from a stack of projectiles has been observed to be as much as twice the value for a single projectile.[19]

The coarsening of the mass distribution at distances of interest in the context of safety is possibly due in part to the proximity of adjacent weapons in a closely-packed stack. The radius of an isolated cylindrical case of mild steel filled with explosive will dilate to about twice its initial size before venting occurs.[6] Mechanical interference between units in a stack will necessarily affect the breakup of the cases. Secondly, initiation of detonation of successive units may be imperfect, being communicated by the shock of case impact. Finally, atmospheric drag acts to filter small fragments preferentially from the mass distribution as the distance from the source increases. The effects of close packing in a stack on the mass distribution and on the initial velocities of fragments must be determined experimentally.

FRAGMENT BALLISTICS

If the mass distribution and the velocity of fragments at the source are known, it is possible to estimate fragment number densities and velocities at impact from an analysis of fragment trajectories. Gravity may have a significant influence on the trajectories of fragments which travel large distances from the source.

Ballistic Properties

Parameters which determine the retardation of fragment velocity in air include the fragment mass, initial velocity, mean presented area, and drag coefficient. The drag force acting on a fragment is proportional to the mean presented area. This area is the average silhouette area projected on a plane normal to the trajectory direction. It can be determined by measurements on recovered fragments using an apparatus known as an icosahedron gage. The gage consists of a light source, collimating and condensing lenses, a crossed wire support for the fragment, and a light level detector. The projected area is measured by means of the light obscured by the fragment in the collimated beam in 16 equally spaced orientations, and the average is taken as the mean presented area. Alternatively, for preformed geometrically regular fragments such as cubes or nearly cubic parallelepipeds whose surface area is known or readily calculated, use can be made of the property that, for a closed surface which is everywhere convex, the mean presented area is one-fourth the surface area.

If the fragments from a given weapon are assumed to be geometrically similar, the mass m and presented area A are related by $M = kA^{3/2}$. Values of k, called a shape factor or ballistic density, may be determined from weight and presented area measurements on fragments recovered from tests of particular weapons. Although the value of k differs from one weapon to another, for forged steel projectiles and fragmentation bombs the average value of 660 grains/in.^{3} (2.60 g/cm^3) has been recommended, while for demolition bombs the value 590 grains/in.^{3} (2.33 g/cm^3) has been applied.

In contrast, for steel cubes and spheres the values are 1080 and 1490 grains/in.[3] based on the density of steel and on the property governing the mean projected area of closed convex surfaces.

The drag pressure acting on a fragment is assumed to follow a velocity-squared law. The retarding force on the fragment is therefore proportional to the product of the mean presented area and the square of the velocity. The dimensionless coefficient of proportionality, the drag coefficient, is determined experimentally as a function of Mach number by firing fragments recovered from detonation tests from a smooth-bore launcher, and observing the decrease of velocity with distance.[10] A plot of drag coefficient C_D against Mach number appears in Figure 3. Its variation with Mach number between subsonic and supersonic speeds is seen to be rather modest despite a peak near the sound speed. A useful approximation for many applications is to take the drag coefficient as constant at its supersonic value of 1.28.

Trajectory Analysis

The motion of a fragment through air under the action of drag and gravity forces is governed by nonlinear equations which cannot be solved analytically. If the force of gravity is neglected, however, the equation of motion can be integrated in the case of a constant drag coefficient to obtain the velocity v as a simple exponential function of distance R from the origin:

$$v = V \exp(-R/L)$$

where the parameter L is defined by

$$L = 2(k^2 m)^{1/3}/C_D\rho$$

if we assume geometrically similar fragments whose presented area and mass are related by the shape factor k defined previously, where ρ is the atmospheric density. The parameter L represents the distance in which the fragment velocity drops to 1/e of its initial value. It can be written as

$$L = L_1 m^{1/3}$$

where L_1 is the corresponding distance for a unit mass. For $k = 2.6\ g/cm^3$ and $C_D = 1.28$, we find that $L_1 = 247\ m/kg^{1/3}$ in air at standard conditions.

A method has been developed for solving the full equations of motion of a fragment, considering the effects of both drag and gravity.[11] An approximate local solution was obtained by splitting the incremental displacement component along the path into two parts, one a basic solution satisfying the equation of motion with gravity absent, and the other a perturbation satisfying the set of linearized residual equations. This amounts to regarding gravity as a perturbing effect on the straight trajectory which results when atmospheric drag alone is considered.

The perturbation solution has been used both as the basis for a numerical integration of the trajectory equations with velocity-dependent drag coefficient, and as an approximate solution for complete trajectories with low angles of launch. The results for distance and velocity at impact depend on the ratio of the terminal velocity in free fall, $(gL)^{1/2}$, to the initial velocity V, where g is the acceleration of gravity.

Integration of the full equations of motion for a variety of initial conditions[12] has shown that the velocity at impact can be estimated from the exponential relation obtained neglecting gravity for launch angles less than a few degrees, and that it is never far below the terminal velocity in free fall for all greater launch angles. This suggests that, as a first approximation, the velocity can be calculated from the gravity-free exponential formula in the near field where it gives values greater than the terminal velocity in free fall, and that it can be taken as the free-fall velocity at all larger distances.

Fragment Number Density

The probability of striking a target at any given position will be determined by the areal density or flux of fragments through the target area projected on a plane normal to the fragment trajectories at impact. When gravity effects are considered, numerical techniques must be utilized even with simplifying assumptions regarding atmospheric drag and the mass distribution of the fragments. If gravity is ignored, however, the fragment flux follows an inverse-square law with distance. Assuming the Mott distribution for number of fragments with respect to mass, the areal density q of fragments of individual mass greater than m, on a surface normal to the ray at distance R, is given by

$$q = (Q_o/R^2) \exp(-(2m/m_o)^{1/2})$$

where Q_o is the total number of fragments per unit solid angle emitted by the source in the direction of the target. In this approximation, consideration of the influence of gravity will extend to its effect on impact speed but not on the terminal direction of the trajectory.

Based on a study of the results of fragment collection and weight analysis from large test explosions of mass-detonating ammunition, Fugelso[16] observed that only the weapons on the sides and top of a rectangular stack appear to contribute to the far-field areal density of hazardous fragments. He recommended that the effective value of Q_o, the number of fragments emitted per unit solid angle from a stack of weapons, be estimated by multiplying the value for a single unit by the number of effective weapons N_E, in turn obtained as

$$N_E = 0.9N_S + 0.1N_T$$

for a stack in the open, or

$$N_E = 0.7N_S + 0.1N_T$$

for the same stack in an earth-covered magazine, where N_S and N_T are the numbers of weapons in the top layer and on the side of the stack facing the direction of interest, respectively.

HAZARD CRITERIA

Fragment hazard levels are determined in terms of two criteria applied jointly. One is the fragment density, on which the probability of striking a target depends. The other, an injury criterion, determines whether injury occurs in the event of a strike.

Strike Probability

The probability of impact by one or more fragments of mass greater than m is readily calculated if the corresponding areal density q is known. The impact process is assumed to be uniformly random in the neighborhood of the point of interest. That is, impact is equally likely on all equal

elements of area in the vicinity of the point. It follows that the probability p of impact on a target of area A_T by one or more fragments of mass greater than m is given by

$$p = 1 - \exp(-qA_T)$$

where q is a function of m as discussed in the preceding section. For a standing man facing the explosion and taking no evasive action, a conservatively large value of 6.2 ft^2 (0.58 m^2) has been recommended for the area A_T.[13]

Since any function of the motion that is usable as a physically realistic injury criterion, such as the impact energy, will increase with increasing mass, the probability of impact by one or more fragments of mass m greater than that corresponding to the injury threshold gives the probability of injury directly. The areal density of injurious fragments considered acceptable under current U.S. standards, $(1/600) ft^{-2}$, corresponds to an injury probability of about 1 percent.

Injury Criteria

A variety of functions of mass and velocity at impact have been proposed as injury criteria.[14,15] In current U.S. explosive safety standards, a value of kinetic energy at impact of 58 ft-lb (79 joules) or more defines a hazardous fragment. This appears to correspond to incapacitation in most exposures over a range of fragment mass from a few grams to several kilograms. Another criterion, one of skin penetration,[15] involves the frontal area as well as the mass and velocity. These injury criteria are plotted in Figure 4, together with curves of the terminal velocity in free fall, $(gL)^{1/2}$.

The skin penetration curves (labeled JMEM in the figure) and the free-fall velocity curves depend on the shape factor k. They are shown for $k = 2.37\ g/cm^3$, an average value for naturally formed fragments from bombs and projectiles, and for twice this value, representing fragments that are more efficient ballistically. Fugelso[16] found that the higher value of k is needed to account for the fragments of least mass collected at various distances from large test explosions [7-9], and is consistent with qualitative observations of the characteristics of the collected fragments. For this higher value of k, $L_1 = 369\ m/kg^{1/3}$.

It may be noted in Figure 4 that the DDESB impact energy criterion is more conservative than the skin penetration criterion for fragments heavier than about 0.2 kg, and less conservative for lighter fragments. It may also be noted, however, that fragments heavier than about 0.1 kg striking at their terminal velocity in free fall would be judged individually hazardous under any of the injury criteria shown.

Suggested Procedure

The following procedure is tentatively suggested for purposes of estimating the fragment hazard from stacks of mass-detonating ammunition:

1. Obtain the Gurney velocity for the explosive filler from Table 2 and calculate the initial fragment velocity V from the Gurney formula with $n = 1/2$ for approximately cylindrical bombs or projectiles.

2. Estimate Q_o, the number of fragments emitted from the stack per unit solid angle, based on the number of effective weapons in the stack and the value of Q_o from a single weapon in the direction of interest (usually the direction perpendicular to the weapon axis).

3. In the absence of data obtained directly from tests with stacks or clusters of weapons, take the average mass m_o to be the same as for an individual weapon, obtained by fitting a Mott distribution to single-weapon arena data, emphasizing the coarse end of the mass spectrum. Assume, however, a shape factor k of 1200 grains/in.[3] (4.74 g/cm^3) to account for the greater ballistic efficiency of fragments from stacks of weapons.

4. Let E_{cr} be the critical level of kinetic energy at impact which defines a hazardous fragment. Determine the mass of the lightest hazardous fragment reaching a specified distance R either from the solution of

$$2E_{cr} = mV^2 \exp(-2R/L_1 m^{1/3})$$

or from the solution of

$$2E_{cr} = gL_1 m^{4/3}$$

whichever gives the smaller value of m. In the former case the terminal energy of a fragment of mass m in free fall is less than E_{cr}, while in the latter case it is greater. With the values E_{cr} = 79 joules and k = 4.74 g/cm^3, it can be seen from Figure 4 that the transition occurs for m = 0.096 kg, approximately.

5. Calculate the areal density of fragments heavier than m reaching distance R from the inverse-square law:

$$q = (Q_o/R^2) \exp(-(2m/m_o)^{1/2})$$

Alternatively, to determine the distance R within which a critical density q_{cr} of hazardous fragments is exceeded, set $q = q_{cr}$ in the above expression, and solve it for R and m simultaneously with each of the two energy expressions given in the preceding step in turn. The desired result will be the larger of the two values of R so obtained.

6. Determine the injury probability p at any distance R from

$$p = 1 - \exp(-qA_T)$$

with $A_T = 0.58\ m^2$. For small values of q, $p = qA_T$ approximately.

The foregoing procedure can readily be adapted for use with an injury criterion other than impact energy, or to an improved treatment of trajectory ballistics. Its overall validity remains to be confirmed by comparison with the results of suitable tests designed for this purpose.

DEBRIS HAZARDS

Compared with the highly developed techniques for evaluating the effectiveness of fragmentation weapons, the rational basis for predicting hazards from secondary fragments such as magazine structure debris and crater ejecta from accidental explosions is much less extensive. The debris produced by a structure surrounding the explosion source will be specific to the building considered. In general, however, such fragments will not be propelled as far as the primary fragments from weapon cases, nor will they usually have as high a level of impact energy as primary fragments reaching the same distance. This is because metal case material in contact with explosive is accelerated far more efficiently than less dense materials and materials separated from the driving explosive by air gaps.

Inhabited buildings exposed to the effects of accidental explosions may be damaged sufficiently to constitute a hazard to occupants from the debris produced. At best, the risk to occupants can only be inferred from the level of damage to the building. At commonly accepted inhabited building distances the blast overpressure is of the order of 1 psi. Wilton[17] has

correlated wood frame house damage with pressure, and found that this level of loading results in damage to the building costing about 5 percent of the building value to repair. Significantly, the damage is mostly superficial, consisting of window glass breakage, cracked plaster, and damage to fixtures and trim.

Crater ejecta from explosions in contact with the ground surface may constitute a debris hazard to exposed persons. Henny and Carlson[18] found that the maximum range of such missiles from test explosions appears to scale as the 0.4 power of explosive weight and that the distances so scaled have the values 70 and 30 $ft/lb^{0.4}$ (29.2 and 12.5 $m/kg^{0.4}$) for rock and soil media, respectively.

Based on an exposed area of 0.58 m^2 for a standing man, Richmond[13] extended Henny and Carlson's results for crater ejecta number density as a function of distance to obtain curves of 1 percent and 50 percent probability of a strike by one or more such missiles, as functions of distance. A relationship similar to that given in the preceding section for the strike probability as a function of primary fragment number density was used. The resulting quantity-distance curves are given in Figure 5, taken from Richmond.[13]

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Table 1 Average weight of fragments weighing more than one grain from steel cylinders* filled with various cast explosives

Source: Reference 3

Explosive	Composition (parts by weight)	Density (g/cc)	Detonation Velocity (m/sec)	$\bar{M}$ (grains)
Baratol	77 Barium Nitrate/23 TNT/0.1 Nitrocellulose	2.49	4900	30
Composition B	59.5 RDX/39.5 TNT/1 Wax	1.68	7900	12
75/25 Cyclotol	Any RDX-TNT combination, in this case 75 RDX/25 TNT	1.69	8070	11.5
H-6	47 RDX/31 TNT/22 Al/5 D-2 Wax	1.73	7460	15.5
HBX-1	40 RDX/38 TNT/17 Al/5 D-2 Wax	1.71	7440	13.5
HBX-3	31 RDX/29 TNT/35 Al/5 D-2 Wax	1.81	7108	18
Minol 2	40 Ammonium Nitrate/40 TNT/20 Al	1.67		19.5
Pentolite	50 PETN/50 TNT	1.64	7530	13.5
PTX-1	30 RDX/50 Tetryl/20 TNT	1.64	7730	12.5
PTX-2	44 RDX/28 PETN/28 TNT 41 RDX/26 PETN/33 TNT	1.67	7930	13
Torpex	45 RDX/37 TNT/18 Al	1.80		13
Tritonal	80 TNT/20 Al	1.71		17
TNT	Trinitrotoluene	1.58	6880	17.5

*9" long, 2" I.D., 2.5" O.D., AISI 1045 seamless, cold rolled, stress relief annealed, Rockwell hardness approximately 100-B.

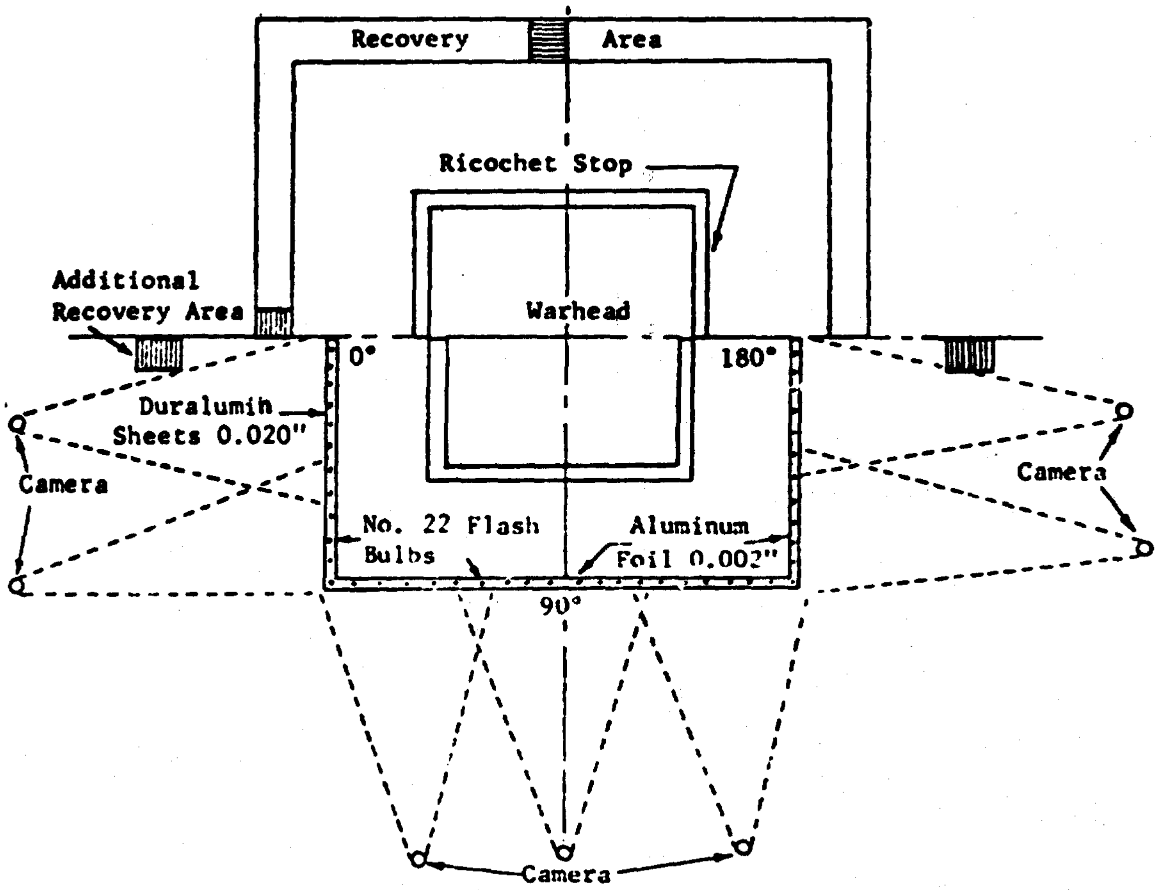
TABLE 2 $V_g(A)$ FOR THE GURNEY EQUATION, $V = V_g(A)/\sqrt{M/C+A}$; V, V_g IN FEET/SECOND

Source: Reference 6

EXPLOSIVE / Source	LLL [17] @ 19 mm $V_g(0.5)$	NOL [5] ALL FRAGS $V_g(0.5)$	NOL [5] TOP 20% $V_g(0.5)$	NOL [5] TOP 50% $V_g(0.5)$	LLL NORMALIZED $V_g(0.5)$	BEST ESTIMATES A = 0.5 $V_g(0.5)$	BEST ESTIMATES A = 0.3 $V_g(0.3)$	TYPICAL H.E.DENSITY g/cc
HMX	9890				9080	9080	8760	1.89
PETN	9787				8990	8990	8670	1.76
RDX	9739 a				8940	8940	8620	1.79
TNT (Cast)	7910	6730	7450	7260	7260	7260	7010	1.60
TNT (Pressed)		6900	7390	7280	7260	7260	7010	
COMP. B (Grade A); 64/36	9014				8280	8280	7990	1.71
COMP. B; 60/40	8940 a	7880	8450	8210	[8210]*	8210	7920	1.70
CYCLOTOL; 77/23	9318				9560	9550	9210	1.75
CYCLOTOL; 75/25	9280 a	7850	8865	8490	8520	8500	8200	1.72
OCTOL; 78/22	9449				8680	8680	8370	1.82
PENTOLITE; (50/50) (Cast)	8849 a	7140	8185	7960	8130	8100	7820	1.69
(Pressed)		7610	8200	7980	8130	8100	7820	
NITROMETHANE	8031				7380	7380	7120	1.14
H-6; RDX/TNT/Al/Wax (47/31/22/5)		7710	8940	8380		8380	8080	1.71

a Interpolated results

* Reference value



Source: Reference 1

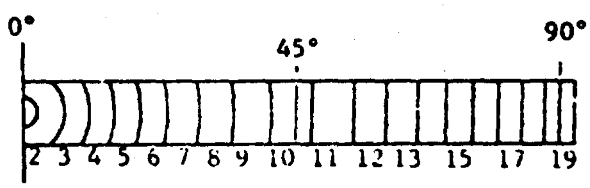
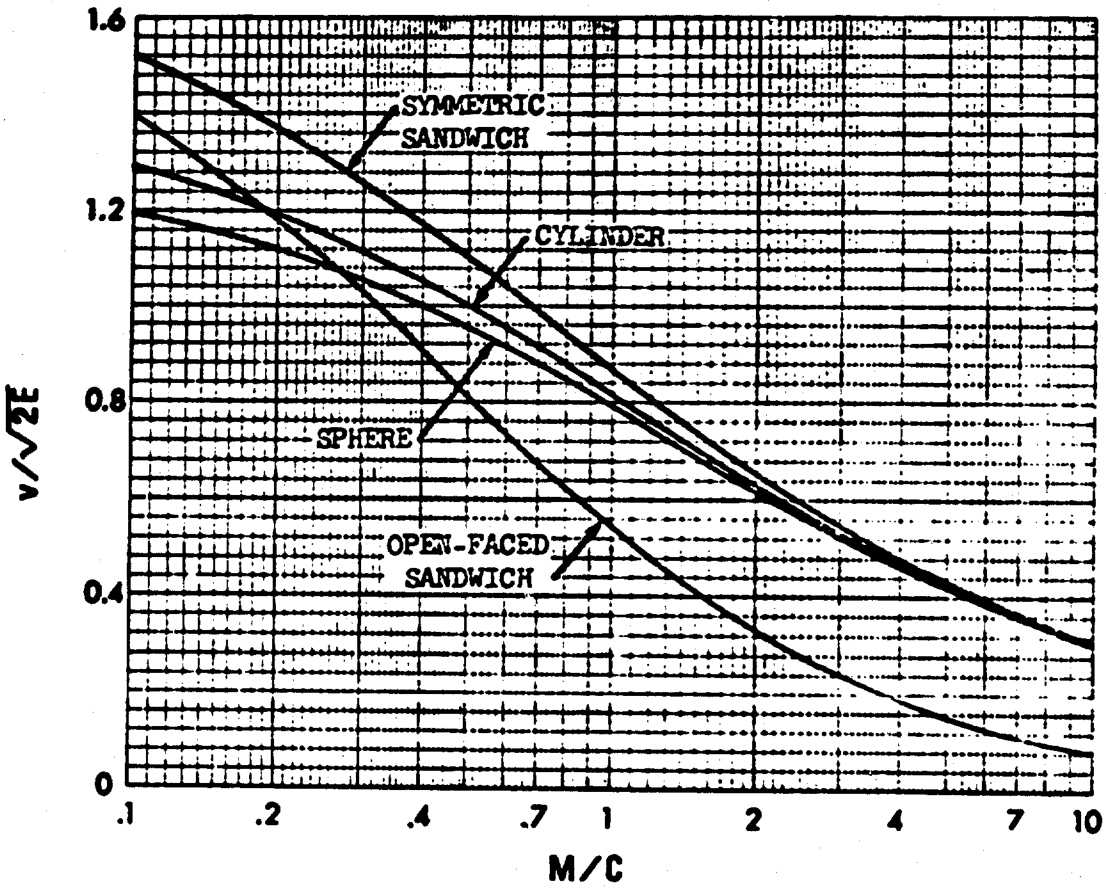


Figure 1 Plan of a Fragmentation Test Area



Source: Reference 5

Figure 2 Velocity of Metal as Function of Loading Factor M/C

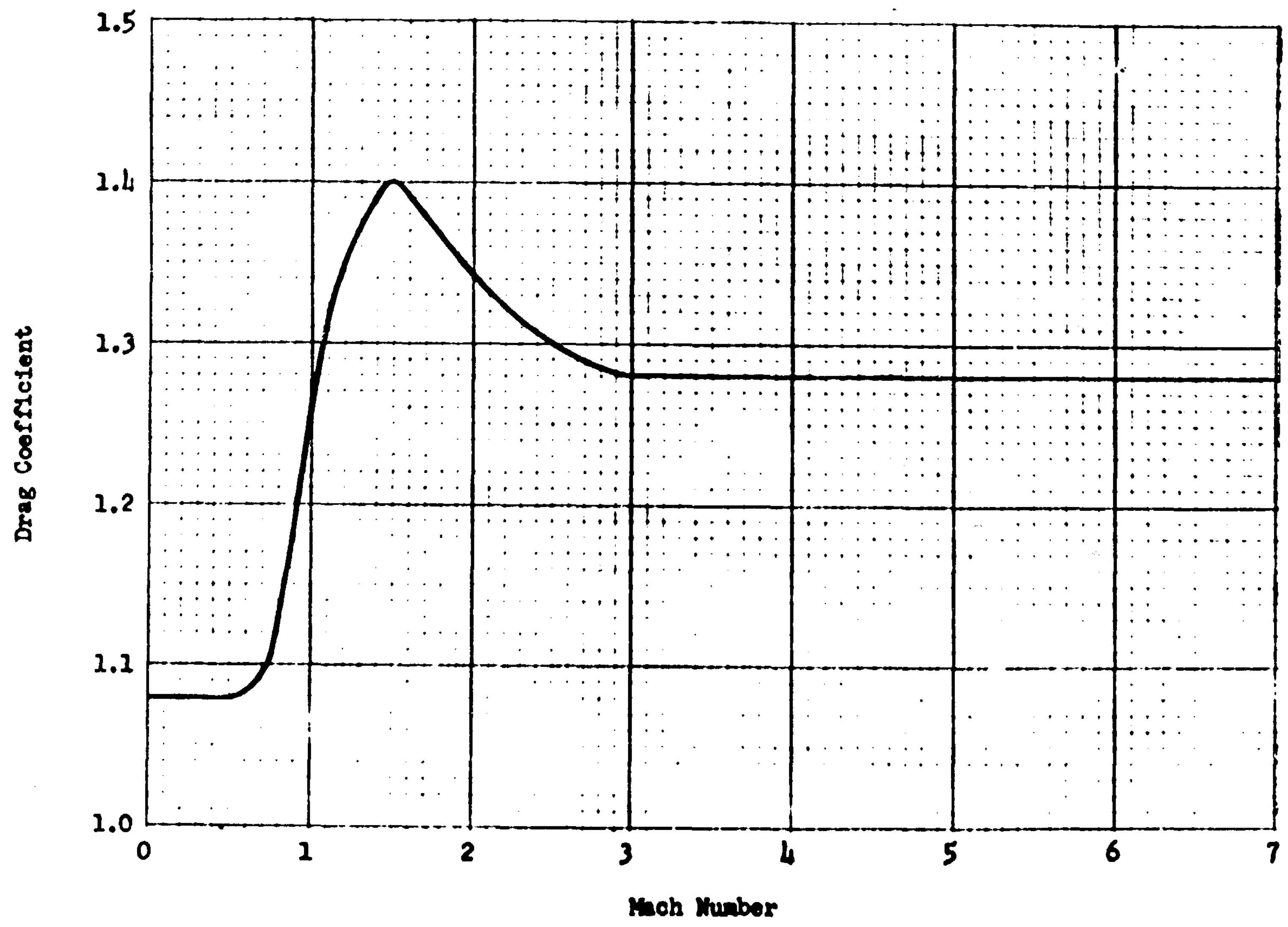


Figure 3 **Drag Coefficient of Fragments**

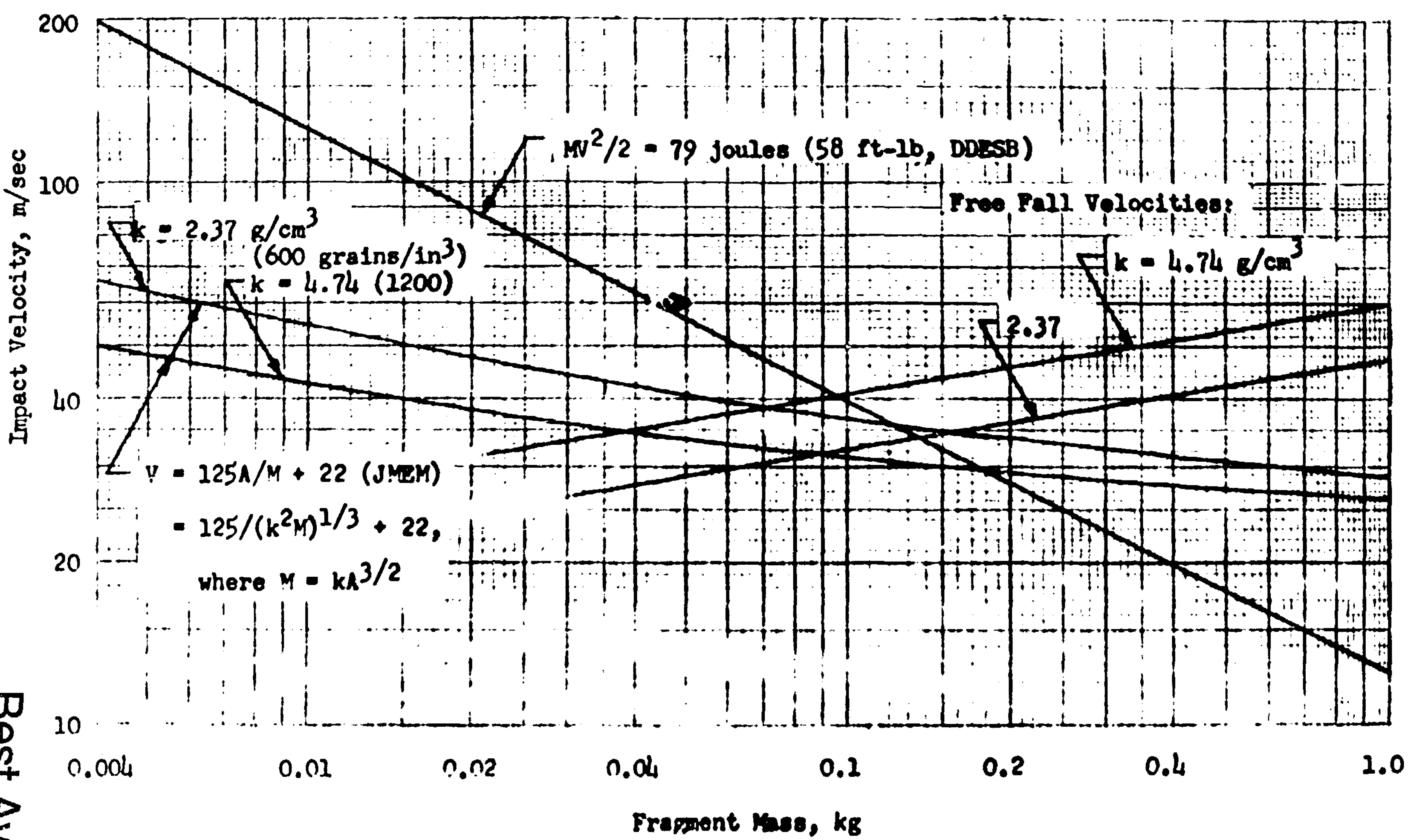
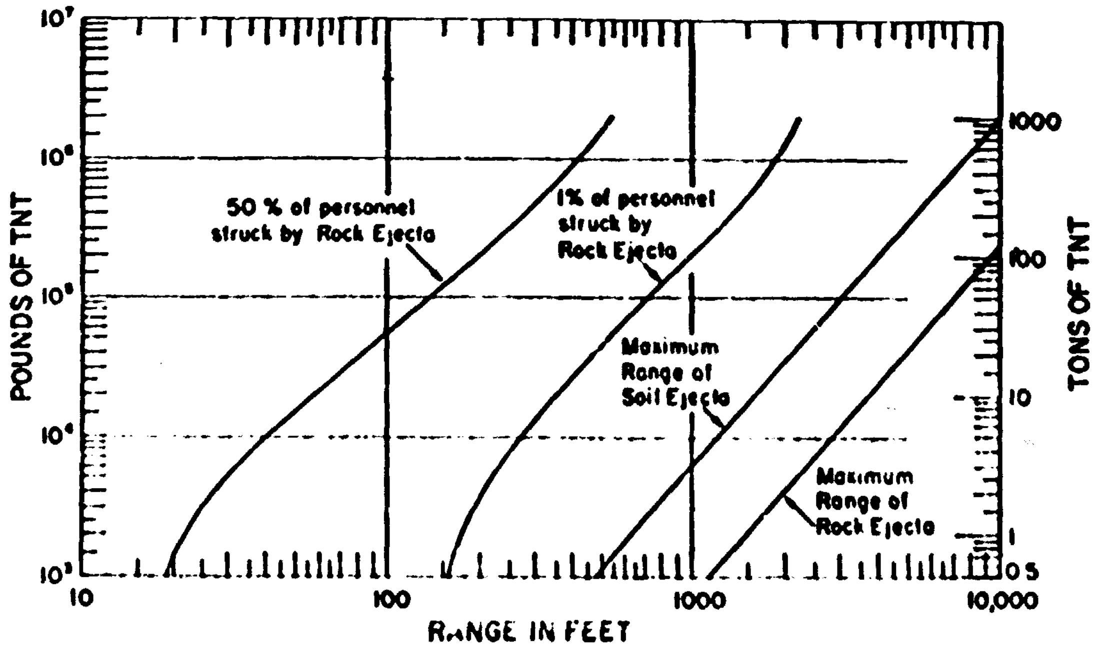


Figure 4 Mass-Velocity Relationships for Fragments



Source: Reference 13

Figure 5 Crater Ejecta Criteria for Personnel in the Open